Studies on bi-directional hydrogen isotopes permeation through the first wall of a magnetic fusion power reactor

IAEA-CRP
Plasma-Wall Interaction with Reduced Activation Steel Surfaces in Fusion Devices
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Table of Contents

1. Background and motivation
2. Experimental facility and setup
3. Hydrogen permeation experimental data and modelling
   3-1. Implications for reactor fuel loop operations
   3-2. Hydrogen transport parameters in the first wall
6. Summary
• Definition of the first wall:

✓ All the fusion experimental devices up to ITER: the first wall is a vacuum chamber wall to separate plasma from the environment.

✓ Power reactors: the first wall is the plasma-facing surfaces of breeding blanket units.

The first walls of existing fusion devices.
Background (2)

• **Blanket concepts include:**
  - water-cooled solid breeder (e.g. Li$_2$TiO$_3$),
  - He-cooled solid breeder (e.g. Li$_4$SiO$_4$),
  - self-cooled liquid breeder (e.g. FLiBe),
  - water-cooled liquid breeder (e.g. Li-Pb)...

• **Typical of the first wall of a fusion power reactor are:**

I. Large surface area: $\sim 10^3$ m$^2$;

II. Made of reduced activation materials;

III. High temperature operation, e.g. $\sim 500^\circ$C for ferritic steel alloys;

IV. Thin wall design to reduce thermo-mechanical stress.

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In most of the recent reactor studies, the first wall is designed to be 5 mm or even less, although these concepts employ various first wall materials.

**Thickness optimization** [2]

Potential Issues with the “thin” wall design

Potential issues, but not quite well addressed, with the “thin” wall design are:

- Plasma-driven permeation (PDP) of D/T fuel into the blanket side
  - Necessitates isotope separation
- Gas-driven permeation (GDP) of bred T into the plasma side (i.e. gas puff)
  - Leads to an unwanted increase in edge plasma density
  - Affect core plasma confinement
Tritium equilibrium pressures in breeders

Assuming 0.1 ppm, the total tritium inventory is of the order of 10 g in the FLiBe blanket.

For blanket employing FLiBe, the tritium thermodynamic equilibrium pressure is \(~10^4\) Pa at 527 °C at a tritium concentration of \(~0.1\) ppm.

\[ C_{T \text{ in wall}} = S(T) \cdot \sqrt{P_{T_2}} \]

Solubility of gases in metals (Sieverts' law):

DIFFUSE-code predictions on FLiBe-blankets
(PDP: 100eV, e$^{16}$ H$^+$/cm$^2$ → 5 mm α-Fe, GDP: 10$^4$ Pa H$_2$ → 5 mm α-Fe at 300 → 800K)

Permeation fluxes

Concentration profiles

GDP ~ 1 Torr liter/s/m$^2$
F82H: Hydrogen PDP and GDP fluxes

Hydrogen PDP and GDP fluxes measured in VEHICLE-1 for a 5 mm thick F82H membrane (under the FLiBe-blanket conditions)

- Hydrogen transport in the first wall is dominated by the flow from the blanket.
- Using the experimental data, the hydrogen recycling rate has been estimated to be $R = 1.025$.

<table>
<thead>
<tr>
<th>Membrane temperature</th>
<th>~500 °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net Implantation flux for PDP</td>
<td>$2.0 \times 10^{16}$ H·cm$^{-2}$·s$^{-1}$ (-100 V bias)</td>
</tr>
<tr>
<td>H$_2$ driving pressure for GDP</td>
<td>~10$^4$ Pa (Fukada) (Thermodynamic equilibrium data)</td>
</tr>
</tbody>
</table>
Evaluation of bi-directional permeation

Conditions for DIFFUSE calculation:

- $T_2$ pressure: $1 \times 10^4$ Pa (Fukada)
- Implantation flux assumptions:
  \[ \Gamma_D = 5 \times 10^{15} \text{ D}\text{·cm}^{-2}\text{·s}^{-1} \]
  \[ \Gamma_T = 5 \times 10^{15} \text{ T}\text{·cm}^{-2}\text{·s}^{-1} \]
- Membrane: 5 mm thick $\alpha$-Fe
- Temperature: 550°C

The tritium release flux at the plasma-facing surface is a total flux from GDP and re-emission.
PDP and GDP under reactor-relevant conditions

PDP and GDP through a 5 mm thick F82H membrane (FLiBe-blanket conditions)

Hydrogen recycling coefficient:

\[ R = \frac{\Gamma_{\text{reflection}} + \Gamma_{\text{re-emission}} + \Gamma_{T-GDP}}{\Gamma_{\text{plasma}}} \]

\[ \Gamma_{\text{reflection}} = \gamma \Gamma_{\text{plasma}} \]  (\( \gamma \) is the particle reflection coefficient)

<table>
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<tr>
<th>Membrane temperature</th>
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<tr>
<td>Net Implantation total flux for PDP</td>
<td>( 1 \times 10^{16} ) ((2 \times 10^{16})) DT·cm(^{-2})·s(^{-1})</td>
</tr>
<tr>
<td>( T_2 ) driving pressure for GDP</td>
<td>( 10^4 ) Pa (Fukada) (Thermodynamic equilibrium data)</td>
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Assuming a particle reflection coefficient of 0.5, the total incident flux is \( 2 \times 10^{16} \) D&T·cm\(^{-2}\)·s\(^{-1}\) and the first wall recycling rate has been estimated to be \( R = 1.018 \).
Potential issues associated with bi-directional DT permeation:

- PDP–D lowers the recovery efficiency of T from the breeder.
- Gas-T permeation increases recycling on the first wall side.

What is necessary to address the bi-directional hydrogen permeation and its associated reactor operation issues?

- Understandings of hydrogen PDP and GDP individually in detail;
- Evaluation of the tritium equilibrium pressure in the fuel recovery loop system;
- Determination of missing hydrogen isotopes transport parameters (solubility, diffusivity and surface recombination coefficient).

No literature data available for the surface recombination coefficient (for F82H), which is important for recycling and retention.
Objectives

I. To understand the mechanisms driving hydrogen isotopes transport processes.

II. To demonstrate experimentally hydrogen transport phenomena that are predicted for the first wall of a fusion power reactor.

III. To establish a database on hydrogen transport parameters for designing fusion power reactors.
2. Experimental facility and setup
Experimental facility

VEHICLE-1

Plasma parameters:
\( n_e: \sim 10^{10} \text{ cm}^{-3} \)
\( T_e: 3\sim4 \text{ eV} \)
Ion flux: \( \sim 10^{16} \text{ cm}^{-2}\text{s}^{-1} \)

Plasma characteristics in VEHICLE-1

Species mix modelling

Ion concentration

H⁺
H₂⁺
H⁻
H₃⁺

Te (eV)

Langmuir Probe data

H₂ Pressure 2 x 10⁻³ Torr

-100V Ne
-100V Te
-150V Ne
-150V Te
-200V Ne
-200V Te

200W ECR power

Ne (10⁹ cm⁻³)

Te (eV)

H₂ Pressure (10⁻³ torr)

Ne (10⁹ cm⁻³)

Te (eV)
**Experimental setup**

**Permeation membrane sample**

- **Thickness**: 0.5-5.0 mm
- **Diameter**: 35 mm
- **Materials**:
  - F82H (Fe-8Cr-2W)
  - SUS304 (Fe-19Cr-11Ni)

**H-plasma**

- The plasma- and gas-driven permeation fluxes are measured by two $H_2$ partial pressure gauges, respectively.
- Ion bombardment energy is provided by a negative bias (-100 V or -50 V).
- **Temperature**: ~200 - 520 °C
3. Bi-directional hydrogen permeation experiments and modelling
Bi-directional permeation

- For the self-cooled breeder blankets, hydrogen isotopes will penetrate through the first wall by plasma-driven permeation (PDP) in one direction and gas-driven permeation (GDP) in the opposite direction.

Important parameters

**GDP:**
- Solubility
- Diffusivity
- External pressure

**PDP:**
- Surface recombination coefficient
- Diffusivity
- Implantation flux
- Reflection coef.
**Hydrogen bi-directional permeation experiment**

- **H plasma:** Te: \(\sim 10\) eV  
  Ne: \(\sim 1.0 \times 10^{10}\) cm\(^{-3}\)  
  Bias: -50V

- **H\(_2\) pressure:** \(\sim 7 \times 10^4\) Pa

- **Membrane:** 0.6 mm thick F82H

- **H GDP flows in the counter direction to H PDP flow and affects the upstream plasma.**

- **The GDP flux has been measured to be** \(9.9 \times 10^{15}\) H/cm\(^2\)/s.
Hydrogen bi-directional permeation modelling

- GDP-T\(_2\) pressure: ~7\(\times\)10\(^4\) Pa
- Ion flux: ~8.5\(\times\)10\(^{15}\) H\(\cdot\)cm\(^{-2}\)\(\cdot\)s\(^{-1}\)
- Membrane: 0.6 mm thick \(\alpha\)-Fe
- Temperature:
  - Gas-facing side: ~580 °C
  - Plasma-facing side: and ~550 °C
- Boundary conditions:
  - Gas side: Sieverts’ law
  - Plasma side: recombination
- Intrinsic trap density: 1%
- Trapping energy: 0.62 eV

The experimental result is in relatively good agreement with the prediction by modelling.
F82H: Hydrogen PDP and GDP fluxes

Hydrogen PDP and GDP fluxes measured in VEHICLE-1 for a 5 mm thick F82H membrane (under the FLiBe-blanket conditions)

- Hydrogen transport in the first wall is dominated by the flow from the blanket.
- Using the experimental data, the hydrogen recycling rate has been estimated to be $R=1.025$.

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</table>

$J_{+} = \frac{D}{L} \sqrt{\frac{J_0}{K_L}}$

$J = -D(T) \frac{dC}{dx}$
4. Modelling on the reactor fuel loop operation with hydrogen isotopes bi-directional permeation through the first wall

4-1. Re-evaluation of hydrogen bi-directional permeation fluxes through the first wall for FLiBe blankets
Re-evaluation of the tritium pressure for FLiBe blankets

Re-evaluation of the tritium flows in a FLiBe loop has been performed, taking into account tritium leakage from the first wall.

Overall tritium inventory: \[ \frac{dM_T}{dt} = J_1 + J_2 - \sum J_3 - J_4 - J_5 \]
## Conditions for analysis:

*Song et al., Plasma Fusion Res. 7 (2012) 2405016.

<table>
<thead>
<tr>
<th></th>
<th>This work</th>
<th>*Song et al.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fusion power</td>
<td>3 GW (Sagara)</td>
<td>1 GW</td>
</tr>
<tr>
<td>Tritium breeding ratio</td>
<td>1.3 (Sagara)</td>
<td>1.25</td>
</tr>
<tr>
<td>Blanket surface area</td>
<td>3000 m$^2$ (Tanaka)</td>
<td>489 m$^2$</td>
</tr>
<tr>
<td>FLiBe flow rate</td>
<td>2.2 m$^3$/s</td>
<td>2.2 m$^3$/s</td>
</tr>
<tr>
<td>Tritium recovery rate</td>
<td>0.99 (Sagara)</td>
<td>0.98</td>
</tr>
<tr>
<td>First wall</td>
<td>5 mm thick F82H</td>
<td>10 mm thick F82H with coatings</td>
</tr>
</tbody>
</table>
| Plasma flux             | $5 \times 10^{15}$ D cm$^2$/s  
                         | $5 \times 10^{15}$ T cm$^2$/s  | No PDP assumed             |
| Calculated tritium      | $1.1 \times 10^3$ Pa | $4.3 \times 10^3$ Pa       |
| pressure                |                     |                            |
4-2. Isotopes effects on hydrogen permeation
Modelling of bi-directional permeation involving multiple hydrogen isotopes

**Bi-directional GDP of the same hydrogen isotope**

T<sub>2</sub> gas

\[ T \quad \text{Membrane} \quad T \]

T<sub>2</sub> gas

Equal pressure: \( p_1 = p_2 \)

- GDP-T<sub>2</sub> pressure: \( \sim 10^4 \) Pa (Fukada)
- Membrane: 5 mm thick \( \alpha \)-Fe
- Temperature: 527 °C
- Boundary condition: Sieverts’ law
- Intrinsic trap density: 1%
- Trapping energy: 0.62 eV

The tritium concentration profiles interact with each other in the two counter flows, finally reaching a flat profile with no net directional flow (quasi-thermodynamic equilibrium).
Bi-directional PDP-D/T and GDP-T$_2$ flows.

- T$_2$ pressure: ~1 Pa
- Implantation flux: $5 \times 10^{15}$ D·cm$^{-2}$·s$^{-1}$, $5 \times 10^{15}$ T·cm$^{-2}$·s$^{-1}$
- Membrane: 5 mm thick α-Fe
- Temperature: 527°C
- Boundary conditions:
  - Gas side: Sieverts’ law
  - Plasma side: recombination
- Intrinsic trap density: 1%
- Trapping energy: 0.62 eV

- The tritium concentration profiles interact with each other in the two counter flows.
- Deuterium flow appears to be independent of these tritium flows, driven by its own concentration gradient.
4-3. Re-evaluation of hydrogen bi-directional permeation fluxes through the first wall for FLiBe blankets
Re-evaluation of the bi-directional permeation process

Conditions for DIFFUSE calculation:
- $T_2$ pressure: $1.1 \times 10^3$ Pa
- Implantation flux assumptions:
  \[
  \Gamma_D = 5 \times 10^{15} \text{ D·cm}^{-2} \text{·s}^{-1} \\
  \Gamma_T = 5 \times 10^{15} \text{ T·cm}^{-2} \text{·s}^{-1}
  \]
- Membrane: 5 mm thick $\alpha$-Fe
- Temperature: 550°C
- Boundary conditions:
  - Gas side: Sieverts' law
  - Plasma side: recombination
- Intrinsic trap density: 1%
- Trapping energy: 0.62 eV

The tritium release flux at the plasma-facing surface is a total flux from GDP and re-emission.
PDP and GDP under reactor-relevant conditions

PDP and GDP through a 5 mm thick F82H membrane (FLiBe-blanket conditions)

**Hydrogen recycling coefficient:**

\[
R \equiv \frac{\Gamma_{\text{reflection}} + \Gamma_{\text{re- emission}} + \Gamma_{T-GDP}}{\Gamma_{\text{plasma}}}
\]

\[\Gamma_{\text{reflection}} = \gamma \Gamma_{\text{plasma}} \quad (\gamma \text{ is the particle reflection coefficient})\]

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<td>Net Implantation flux for PDP</td>
<td>(1 \times 10^{16} \text{ (2} \times 10^{16} \text{ ) DT} \cdot \text{cm}^{-2} \cdot \text{s}^{-1})</td>
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<tr>
<td>(T_2) driving pressure for GDP</td>
<td>(1.1 \times 10^{3} \text{ Pa (This work)})</td>
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</table>

Assuming a particle reflection coefficient of 0.5, the total incident flux is \(2 \times 10^{16} \text{ D&T} \cdot \text{cm}^{-2} \cdot \text{s}^{-1}\) and the first wall recycling rate has been estimated to be \(R = 1.006\).
5. Experimental work on hydrogen isotopes transport parameter

5-1. Gas-driven permeation (GDP) experiments for the evaluation of solubility and diffusivity
Gas-driven permeation

Solubility of gases in metals (Sieverts' law):

\[ C = S(T) \cdot \sqrt{p_{H_2}} \]

\( S(T) \): Sieverts’ constant as a function of temperature

\( p_{H_2} \): hydrogen pressure

Diffusion limited gas-driven permeation flux:

\[ J = -D(T) \frac{dC}{dx} \]

\[ = \frac{D(T)S(T)}{L} \left( \sqrt{p_{H_2\text{-upstream}}} - \sqrt{p_{H_2\text{-downstream}}} \right) \]

\( L \): membrane thickness

\( D(T) \): diffusion coefficient

\( p_{H_2\text{-downstream}} \): hydrogen pressure at the low pressure side, usually \( p_{H_2\text{-downstream}} \approx 0 \)

Permeability for GDP:

\[ P(T) \equiv D(T)S(T) \]
Diffusion coefficient from GDP

3 methods to evaluate the diffusion coefficient, D:

1. Transient curve fitting method\textsuperscript{[1]}
   Solving the diffusion equation:
   \[
   \frac{\partial C(x,t)}{\partial t} = D(T) \frac{\partial^2 C(x,t)}{\partial x^2}
   \]
   \[
   J(t) = \frac{D(T)S(T)\sqrt{P_{H_2}}}{L} \times \left[1 + 2 \sum_{n=1}^{\infty} (-1)^n \exp(-D(T)\frac{n^2 \pi^2}{4}t)\right]
   \]

2. Time lag method\textsuperscript{[2]}:
   \[
   t_l = \frac{L^2}{6D} \quad J(t_l) \approx 0.63J(t_\infty)
   \]

3. Breakthrough time method\textsuperscript{[2]}:
   \[
   t_b = \frac{L^2}{D\left(\frac{1}{6} - \frac{1}{\pi^2}\right)} \approx \frac{L^2}{15.3D}
   \]

**SUS304: Validation of the experimental setup and data analysis**

**GDP through 0.65 mm thick SUS304**

**Permeability**

\[ P(T) = D(T)S(T) = \frac{J_{GDP}}{\sqrt{P_H}} \]

**Diffusion coefficient**

\[ D = 5.5 \times 10^{-3} \exp\left(\frac{-0.57 \text{ [eV]}}{kT}\right) \quad [\text{cm}^2 \cdot \text{s}^{-1}] \]

**Permeability**

\[ P = 9.6 \times 10^{-10} \exp\left(\frac{-0.62 \text{ [eV]}}{kT}\right) \quad [\text{mol} \cdot \text{cm}^{-1} \cdot \text{s}^{-1} \cdot \text{Pa}^{-1/2}] \]

**Solubility**

\[ S = 1.8 \times 10^{-7} \exp\left(\frac{-0.05 \text{ [eV]}}{kT}\right) \quad [\text{mol} \cdot \text{cm}^{-3} \cdot \text{Pa}^{-1/2}] \]

A linear relation between GDP flux and the square-root of upstream pressure has been found at all the temperatures examined in this work.

**GDP is diffusion-limited model:**

\[ J_{\text{GDP}} = -D(T) \frac{dC}{dx} = \frac{D(T)S(T)}{L} \sqrt{p_{H_2}} \]

Even for a 5 mm thick membrane, reactor-relevant, hydrogen GDP has been found to be diffusion limited.
The diffusion coefficient of H through F82H has been evaluated from the transient permeation behavior. A breaking point has been found for the diffusion coefficient data, which we attribute to the trapping effect.

In the presence of traps:

\[
\frac{\partial C(x,t)}{\partial t} = D(T) \frac{\partial^2 C(x,t)}{\partial x^2} - \frac{\partial C_i(x,t)}{\partial t} = D_a(T) \frac{\partial^2 C(x,t)}{\partial x^2}
\]

Measured diffusion coefficient:

- \(~250 \, ^\circ C\) \(D = 7.5 \times 10^{-4} \exp\left(\frac{-0.14 \, \text{[eV]}}{kT}\right) \, \text{[cm}^2\cdot\text{s}^{-1}]\)
- \(< 250 \, ^\circ C\) \(D = 1.9 \exp\left(\frac{-0.50 \, \text{[eV]}}{kT}\right) \, \text{[cm}^2\cdot\text{s}^{-1}]\)
F82H: hydrogen permeability and solubility

The permeability and solubility of H in F82H have been evaluated from the steady state temperature dependent GDP data.

\[ P = 2.3 \times 10^{-10} \exp\left(\frac{-0.39 \text{ [eV]}}{kT}\right) \text{ [mol cm}^{-1}\text{s}^{-1}\text{Pa}^{-1/2}] \]

\[ S = 3.1 \times 10^{-7} \exp\left(\frac{-0.25 \text{ [eV]}}{kT}\right) \text{ [mol cm}^{-3}\text{Pa}^{-1/2}] \]

5-2. Plasma-driven permeation (PDP) experiments for the evaluation of surface recombination coefficients
Steady state plasma-driven permeation models

**Recombinative desorption flux:**

\[ J_- = K_r \cdot C_H^2 \]

*(\(C_H\) is hydrogen atomic concentration at the upstream surface)*

**Flux conservation:**

\[ J_0 = J_- + J_+ \]

\[ (J_- \gg J_+) \]

**Diffusion**

\[ J_+ = \frac{d}{L} J_0 \]

\[ J_+ = \frac{D}{L} \sqrt{\frac{J_0}{K_r}} \]

\[ J_+ = \frac{K_L}{K_r + K_L} J_0 \]
The ion species mix has been estimated by modelling.

- $\text{H}_3^+$ is the dominant ion species in the electron temperature range of the experiments.
- The concentration of $\text{H}^+$ increases as the increase of electron temperature and becomes the dominant species when the electron temperature is higher than 4 eV.
F82H: membrane thickness effects on steady state PDP

Steady state PDP data for F82H membranes at ~220 °C and ~500 °C (-100 V bias)

- The steady state permeation flux is inversely proportional to the membrane thickness, meaning that the hydrogen transport process is in the recombination-diffusion limited regime.

### RD limited flux:

\[
J_+ = \frac{D}{L} \sqrt{\frac{J_0}{K_r}}
\]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>220 °C</td>
</tr>
<tr>
<td>Temperature</td>
<td>500 °C</td>
</tr>
<tr>
<td>( Te )</td>
<td>~3 eV</td>
</tr>
<tr>
<td>( ne )</td>
<td>~1x10^{10} cm(^{-3})</td>
</tr>
<tr>
<td>Net Implantation flux</td>
<td>~5x10^{15} cm(^{-2})s(^{-1})</td>
</tr>
<tr>
<td>Permeation flux</td>
<td>~10^{13} cm(^{-2})s(^{-1})</td>
</tr>
<tr>
<td>PDP flux ratio</td>
<td>~10^{-3}</td>
</tr>
</tbody>
</table>
The surface recombination coefficient of H on F82H has been measured from the steady state temperature dependent PDP data.

The surface recombination coefficient:

\[ K_r = 4.8 \times 10^{-21} \exp\left(\frac{0.48 \text{ [eV]}}{kT}\right) \text{[cm}^4\text{·s}^{-1}] \]

- The recombination coefficient for F82H has been estimated for the first time from the experimental data.
5-3. Surface condition effects on PDP
Earlier studies related to surface condition effects

Surface condition effects interpretations in earlier studies:

(1) changes in surface recombination coefficient due to sputtering or deposition of contaminations (Causey et al.);

(2) changes in surface recombination coefficient and diffusivity due to ion-induced surface defects (Winter et al.).

This work will:

(1) propose a new hypothesis to interpret the surface contamination effects and;

(2) propose a new model to describe the surface area/roughness effects.
(1) Surface contamination effects

(a) Clean surface (RD-regime)

(b) Thin impurity film

(c) Thick impurity film

A new hypothesis:
Comparing the implantation range and the thickness of the impurity layer.
The contamination effects have been investigated by the surface oxidization method.

\[ \text{O}_2 \text{ gas } 1 \times 10^{-2} \text{ Pa} \]

\[ \text{at 450-500 } ^\circ \text{C} \]

- **PDP with clean surface**
- **Surface oxidization**
- **PDP with oxidized surface**

- After oxidization, it takes longer time for the permeation flux to reach steady state, suggesting a lower effective diffusion coefficient for the oxidized samples.

\[ \text{Chemical sputtering of surface oxides: } 2\text{H} + \text{Fe}_x\text{O}_y \rightarrow \text{H}_2\text{O} + \text{Fe}_x\text{O}_{y-1} \]

**Diagram:**
- Impurity layer
- Membrane
- Temperature vs. time graph
- Water vapor pressure vs. time graph
- Reaction equation for chemical sputtering
Surface contamination effects on PDP (2)

Surface composition of the samples are examined by X-ray photoelectron spectroscopy (XPS).

Polished surface

After 45 min oxidization

Hydrogen implantation profile

The thickness of the impurity layer is larger than the implantation range.
Surface area effect on PDP behavior

(a) PDP through a flat surface

Surface area $A_0$

(Net implantation)

Surface area $A_1$

(Re-emission)

(b) PDP through a modified surface

Surface flux ratio:

$$J_1/J_0 = A_0/A_1$$

Surface concentration ratio:

$$J_0 \approx J_{0-} = K_r C_0^2$$

$$J_1 \approx J_{1-} = K_r C_1^2$$

$$\Rightarrow C_1 / C_0 = \sqrt{J_1 / J_0}$$

$$J_+ = -D(T) \frac{dC}{dx} \quad \Rightarrow \quad \text{The permeation flux ratio:} \quad \frac{J_{1+}}{J_{0+}} \propto \frac{1}{\sqrt{A_1 / A_0}}$$
To verify surface area effect, PDP experiments have been performed using samples with well controlled surface morphology.

Three samples:
- Flat surface
- Modified surface-1
- Modified surface-2

Surface area ratio:
- Modified surface-1: $A_1/A_0=6.4$
- Modified surface-2: $A_1/A_0=3.2$

Effective thickness:
- Modified surface-1: $4 \text{ mm} < L_{\text{eff}} < 5 \text{ mm}$
- Modified surface-2: $4 \text{ mm} < L_{\text{eff}} < 5 \text{ mm}$
The measured steady state permeation flux has been found to be inversely proportional to the square root of surface area, which is in good agreement with the model prediction.
Compared with the polished surface, the steady state PDP flux for the plasma modified surface has been found to decrease by a factor of ~1.7, indicating a surface area ratio of $A_1/A_0=\sim2.8$.

The surface area is increased due to the surface modification.
A combined effect has been observed as follows:

\[
\text{Combined surface effect} \approx \text{oxidization effect} \times \text{surface area effect}
\]

\[
\approx 3.2 \quad \approx 1.4 \quad \approx 2.5
\]
Summary and future plans

I. Bi-directional hydrogen permeation has been demonstrated for the first time in a laboratory-scale steady state plasma facility.

II. Revaluation of the dynamic tritium pressure in a fuel recovery loop has been performed.

III. Hydrogen PDP and GDP through F82H have been investigated under some of the reactor-relevant conditions.

IV. Hydrogen transport parameters have been evaluated for F82H, including the recombination coefficient.

V. Surface condition effects on hydrogen permeation have been examined and a new model has been proposed to interpret the data.

VI. Future plans include: deuterium PDP and GDP experiments to evaluate the isotope effects and also surface coatings effects (i.e. W-coatings).